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Methodology for the assessment of structural complexity in global production networks

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Abstract

The structure of production networks is mainly determined by the amount of production sites, the number of people working in these production sites and the distribution of products and production processes. Due to the dynamic and unpredictable changes in global market requirements production networks have become more and more complex driven by the growth of multinational companies through acquisitions and set ups of production plants. This paper presents an approach to design production networks with an optimal level of structural complexity in order to increase the efficiency of production processes around the world. The approach consists of two basic elements: firstly, the structural complexity is captured via characteristic parameters and quantified. The main characteristics of a production network such as the amount of production sites, the number of employees and the product and process distribution form the basis for the quantification. The second cornerstone is set by the intelligent visualization of the structural complexity with respect to organizational and communication aspects. Organization and communication structure of a company can be optimized comparing different production network scenarios, hence increasing the overall efficiency within global production networks. A validation of our approach is presented using a data set of a recently conducted industry project. Different network scenarios of a global manufacturer in the mechanical engineering field are compared to point out design rules for the optimization of structural complexity within the company.

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1. Introduction

The environment for companies worldwide is complex. According to a study by IBM, the majority of CEOs expect the world to become even more complex in the next years. In order to deal with this situation, CEOs develop creative approaches to change business models and introduce innovative ways for leading and communication. [1]

The mayor challenge for a CEO is the decision overload based on the amount of task and decisions he or she has to deal with. Compared to the 70 decisions an average person has to make per day, a CEO works on approximately 139 tasks and makes 250 decisions. Due to the amount of decisions, most of them have to be done in short time. 50 percent of the decisions of a CEO are

made in less than 9 minutes and only 12 percent take longer than an hour. [2]

In this paper, we want to support the decision process for the complex problem of designing internal production networks of globally active companies by defining a set of parameters to characterize the structural complexity in production networks. Based on those parameters indicating communication processes, we develop an assessment method to compare the structural complexity of network scenarios.

2. Requirements

This paper is divided into two parts. The first part is dedicated to the measurement of complexity in global production networks. The measurement should be done capturing parameters representing complexity-driving

elements of production networks. These parameters should cover the complexity on three levels: production line (shop floor), organization of the production sites and network structure. The second part includes the visualization of the structural complexity by means of communication processes in production sites as well as in global production networks when comparing a set of scenarios.

Therefore, the tasks pursued in this paper are:

- Definition of complexity parameters to capture the complexity of global production networks
- Development of a visualization concept to incorporate complexity in the network design process

The concept to indicate structural complexity by visualizing communication processes will be validated using data from an industry project with a global manufacturer.

3. State of the Art

3.1. Measuring structural complexity

The term “complexity” is often used to describe objects we perceive as difficult, nontransparent and incomprehensible. These objects have in common that they show a variety of different behavioral patterns as well as a high degree of uncertainty, both existing either combined or separately. [3]

Complexity appears in two different ways [4]: structural complexity arises from the number of elements and relations of a system and the different kind of states these elements and relations can possess. Therefore, the term structural complexity expresses the variety of a system. The other type of complexity is the functional complexity and describes how complexity is handled by a system. It indicates the gap between the actual problem solving requirements and the systems potential to handle complexity, limited by cognitive and capacitive barriers or resentments. [3],[5-6]

The focus of this paper lies on the former type of complexity because scenarios consisting of elements and relations of network configurations are assessed. The measures presented are therefore designed to cover the structural complexity of a system.

Klaus calls the type and amount of relations between elements connectivity. Apart from this measure for relations, he names the variety of elements complicity. With this distinction, it can be shown that complicity is always a cause for complexity. Then again, complexity can also exist with few elements in a system (a low level of complicity). [7]

Another way to measure structural complexity is given by Kornwachs and Lucadou who define two different kinds of densities: the connection density and the structural density. The connection density is created

by dividing the current relations of a system by the maximum number of relations of one kind of system. The structural density is defined by ratio of the sum of all connection densities for all kinds of connection and the total amount of different kinds. This leads to a structural density of “1” if all possible relations are carried out or “0” if none is carried out [8].

Entropy, a measure developed by Shannon, captures the amount of information as well as the degree of chaos in state spaces or event spaces. The idea behind this measure is that a system is featured with a higher order if there is a higher probability for certain states to appear than for others. Therefore, entropy is defined in a way that it becomes “0” for all probabilities of all possible states except for one with the value “1” being “0”. In case the probability of all events is the same, the maximum value for the entropy of the system online depends on the absolute number of events [9], [10].

Regarding the assessment of network configurations, Klaus delivers a valuable approach for the purposes of this paper by dividing the structural complexity in one parameter to measure the number of elements (plurality) and one parameter to measure the types and amounts of relations (diversity). Based on this idea, we will develop a set of characteristic parameters for this paper to determine the plurality and the diversity of production networks on three levels: production level (shop floor), site level and network level.

3.2. Assessing communication structures in organizations

Communication plays a key role in the management of networks and therefore also for handling complexity. In this chapter, we present different research results from systems theory, architecture and biology that stress the importance and the limitations of communication in organizations.

According to Luhmann, communication can be interpreted as a systems way to self-energize. The stimulus caused by a social interaction necessary for communication leads to the formation of structures that prove themselves under given conditions. When the process of communication is kept running, it creates two phenomena: redundancy and difference. Redundancies arise from the processes of sharing information and lead to an overspill that helps to prevent losing information. Differences describe a situation where the information contained in the communication process doesn't match. It represents a mechanism of self-correction to prevent spreading errors and mistakes. Communications results in the formation of systems while generating thematic structures and redundant contents. [11]

Allen and Henn stress that awareness is built through communication and therefore forms an important factor

for management. Using the example of a product development process, they point out that the exchange of information in any kind of way is crucial for a successful implementation. According to the authors, personal communication is highly beneficial, counting up for 80 percent of the information concerning new ideas. Therefore, the success of communication processes decides whether the goals of a project are met or not. Since communication arises from the interaction of people, Allen and Henn promote the idea of reconfiguring the physical working space to support the critical communication processes. [12]

Dunbar et al. find that the size of the neocortex, a part of the brain linked to the social capabilities of primates, defines the maximum number of relationships a primate can have. Analyzing the size of different primates, Dunbar et al. state that the size of the neocortex of humans correlates with 150 relationships, a number that can be verified by the size of ancient hunter-gatherer communities. Another result are the circles of intimacy, categorizing relationships based on the intimacy a person has with another. He finds that close relationships can only be maintained with a group of up to five persons. Both characteristics, the maximum number of relationships and the size of the close group are limited by the cognitive capacity of the brain as indicated by the size of the neocortex. [13]

Summing up the results of these research approaches, communication influences the structure of systems like organizations. Furthermore, it is highly important for the management of processes like manufacturing processes in global networks to build up an efficient communication culture. Lastly, communication is limited to a maximum number of direct and indirect persons due to cognitive barriers and the complexity of communication in huge networks. We assume that by measuring the ability for communication of a network, we detect how successfully complexity can be handled in production sites and global networks under given restrictions.

3.3. *Designing production networks*

Another aspect to look at is the existing approaches for the design of production networks and the targets they focus on. Here, two main research directions can be distinguished. The first direction includes approaches for the optimization of production networks using specifically design algorithms. For a selection of such approaches we refer to Schuh et al. [14]

The second research direction includes approaches that focus on the value creation by developing evaluation models. Since the aim of this paper is to define a set of complexity and communication evaluation tools, the following approaches belong to the latter direction.

Merchiers develops a method to design and select different network structure alternatives by supporting an evaluation procedure. The approach puts emphasis on the maximization of the company's cash flow, using an evaluation of the cost structure of a production network. Merchiers develops an evaluation procedure with three levels, each having a specific cost structure: module level, site level and network level. Furthermore, the evaluation procedure consists of a testing routine that includes the financial feasibility, the allocation of production sites and different network structure alternatives. [15]

The approach of Ude consists of an evaluation of globally distributed value networks, being used as a support tool for decision-making. One of the main elements is a multi-dimensional target system that aims to design networks in accordance to several targets. The evaluation procedure contains two fundamental tools: a qualitative support tool for decision-making and a simulation model for quantitative evaluations. By combining these two tools, it is possible to define a ranking of network configurations whose scenarios can be tested for robustness using sensitivity or scenario analysis. [16]

Lanza et al. create a software-based planning tool and an optimization method for versatile value networks. In this approach, multidisciplinary between production, logistics and organization is a key goal. Three central elements are on target: determining the need for transformation, evaluating transformation enablers and creating a continuous monitoring concept for networks. These three central elements are integrated into a control loop for versatile value networks. [17]

It can be seen that production network design approaches mostly include monetary targets such as costs or revenues as described for the approach of Merchiers. Further aspects like multi-dimensional target systems Ude introduced improve the accuracy of design methods and help to select scenarios based on a broader understanding of important network features. A continuous improvement procedure as the one presented by Lanza et al. supports the idea of the permanent need for adaption given by the characteristics of a complex environment. The approaches at hand emphasize important aspects of global production networks, but do not contain ways to measure, visualize and incorporate complexity in the design process. This paper demonstrates a way to integrate complexity in the design process, taking conventionally designed network scenarios as a starting point to visualize different levels of complexity.

4. Methodology for the assessment of structural complexity in global production networks

The methodology developed integrates two core elements, the characteristic parameters to measure structural complexity and the visual concept to evaluate different network scenarios into an assessment procedure. These elements as well as the procedure are described in this chapter.

4.1. Characteristic parameters

We determine the plurality and the diversity indicating the structural complexity of global production networks, distributed over three different levels by defining characteristic parameters.

The first level we describe is the production program for each production site of a production network. To measure the structural complexity of the production program, we distinguish two characteristic parameters: the production volume (plurality) and the number of product groups (diversity) each site has to produce.

By expanding the view from the production process to the whole production site, we also have to take organizational and communication processes into account. Hence, the second level of characteristic parameters consists of the number of direct and indirect FTEs (full-time equivalents) representing the plurality and the hierarchical structure of the production site (number of hierarchical levels, span of leadership) representing the diversity.

On the third level, the holistic network structure itself is observed. Here, the characteristic parameters for measuring the structural complexity are the number of production sites (plurality) and the number of relationships between them (diversity).

Plurality	Diversity
Production program	
Production volume at production site i	Number of product groups at production site i
Organization of the production site	
Number of direct FTEs at production site i	Span of leadership at production site i
Number of indirect FTEs at production site i	Number of hierarchy levels at production site i
Network structure	
Number of production facilities	Number of relationships in the network

Fig. 1. Summary of the characteristic parameters to measure structural complexity

In Fig. 1, a summary of the characteristic parameters and the corresponding levels in a production network is presented. All of these indicators directly or indirectly influence the intensity and range of communication processes in a network. Therefore, in the following

visualization concept, some parameters are directly, some indirectly observed.

4.2. Visualization concept

The visualization concept used is divided into three elements, each illustrating selected complexity parameters related to communication in production networks.

The first element is a tree map of the network configuration representing the resource capacity used in each production site of the network. Tree maps, introduced by Johnson and Schneiderman, are based on an algorithm that subdivides hierarchical data (such as the resource capacity per site) recursively, mainly using the standard shape of a rectangle. [18] The resource capacity used is based on the specific production program, therefore representing two characteristic parameters: the production volume and the number of product groups of each production site. This tree map indicates two things: First, it shows what kind of production volume/number of product groups a production site has to communicate about. Second, it is an indicator for the total landed costs of a site, given that each location of a production site has different labor costs. The total landed costs are commonly used in conventional design approaches to decide which network scenario is optimal.

The second element is a communication graph based on the approach of Pentland for visualizing team work relationships. [19] The concept was adapted to be suitable for graphing the intensity of communication between the production sites of a network based on the necessary information exchange for process and volume splitting. Therefore, two characteristic complexity parameters are used: the production volume and the number of product groups define the intensity of communication between production sites. In this graph, three kinds of intensity are distinguished. No involvement of a production site in the network is indicated by missing links to that site. Medium intensity, being illustrated by thin, blue lines, takes place below a network specific threshold of production volume/product groups at a specific site. Process and volume splitting above this threshold is marked by thick, red lines. Furthermore, the headquarter of a network coordinated solely by one company is indicated with the letters "HQ". Leaving out headquarter from a production network might lead to a situation where important information beneficial to handle complexity is not available.

The third element is a graph developed to express the internal communication in a production site, based on the span of leadership and the product group related number of indirect FTEs. This graph shows the number of supervised employees and product group each indirect

FTE is responsible for, representing two characteristic complexity parameters. The indicator measured is the maximum distortion (maximum distance) of the described ratio (span of leadership over product group related number of indirect FTEs) of one production site value to the all over average. The higher the value of the maximum distance the more effort has to be put on the internal communication of these deviating production sites. This leads to a higher level of complexity in the network.

Figure 2 shows the three different elements of the visual concept.

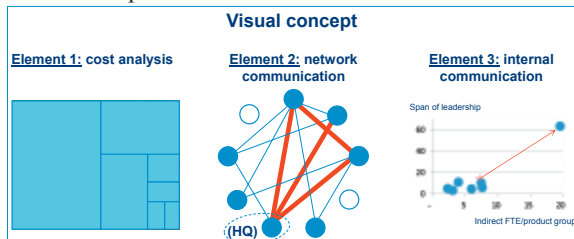


Fig. 2. Visual concept for the assessment methodology

4.3. Assessment of global production network scenarios

Using the visual concept described above, an assessment methodology is developed to analyze communication-dependent structural complexity in different global production network scenarios. The methodology consists of three steps following the structure of the visual concept and a final goal-based scenario analysis.

The first step contains a comparison of the total landed costs based on the number of different production sites and the amount of necessary resources. The different scenarios are evaluated expressing the total landing costs of each scenario as a percentage of the costs of the priciest scenario. The order resulting from this step starts with the least expensive scenario leading to the one with the highest costs.

The second step is the analysis of the network communication necessary for each scenario. It shows the intensity of communication in a scenario between two sites based on the distribution of production volume and product groups. This intensity of communication corresponds to the capability to handle structural complexity in the network. Comparing different levels of medium and high intensity, an order of the considered network scenarios is determined that might differ from the order based on studying different cost structures.

The final step takes the internal communication of a production site into account. Research has shown that efficient communication structures are limited by the capability of the brain to process relationships. By adapting this concept to an organization such as an

production site, it can be stated that strong deviations from the average value of responsibility of indirect FTEs for employees and resources lead to inefficient communication structures and therefore to lower abilities to handle complexity. Regarding the maximum distance described above as an indicator for this kind of inefficiency, another order of the considered scenarios can be defined.

Lastly, the different orders resulting from the three steps of the visualization concept have to be interpreted according to the goals of the company running the production network. One important factor can be that all important sites such as headquarters are involved in the favored scenario.

5. Validation of the assessment methodology

The example used to validate the assessment methodology is based on an industry project of the WZL () with a gear box producer that planned to optimize its global production network. Out of the different scenarios suggested during this project, three are taken to demonstrate the impact of the assessment methodology present (Fig.3).

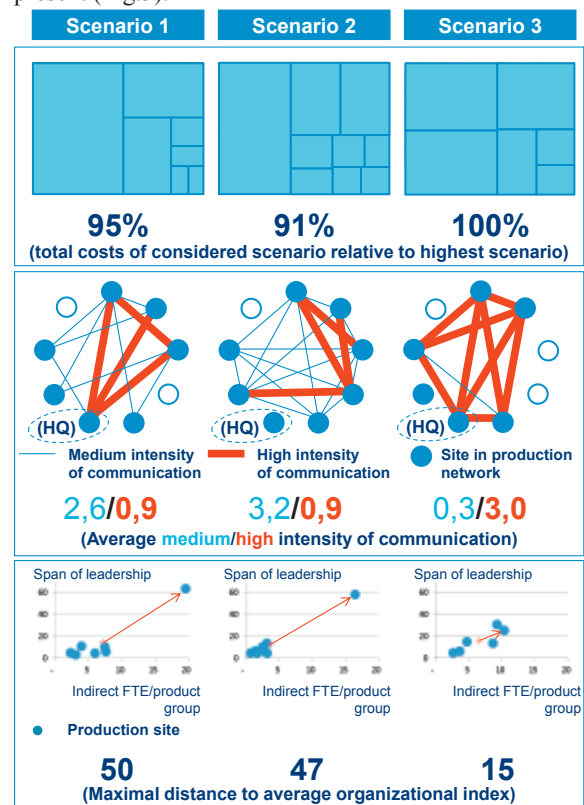


Fig. 3. Validation of the assessment methodology using data from an industry project with a gear box manufacturer

The distribution of the production analyzed in the first step within the network leads to a high level of total landed costs in scenario 3 and lower levels of the total landed costs in scenarios 1 and 2 with 2 having the lowest. Therefore, based on the cost analysis as the only indicator, scenario 2 would be chosen.

In the second step, scenario 3 shows in fact the highest intensity of communication within the network whereas scenario 1 and scenario 2 only differ from the level of medium intensity. Furthermore, in scenario 2 the headquarters are not integrated in the network leading to an unfavorable situation for complexity handling. As a result, the order according to the second graph favors scenario 3 over scenario 2 (where the medium intensity is higher) over scenario 1.

The analysis of step three points out that the deviation from the average maximum distance value is the lowest for scenario 3 while the values for scenario 1 and scenario 2 are significantly higher. The difference between these two is negligible.

Finally, the interpretation of the different scenario orders from the three steps leads to a differentiated picture of each scenario. Scenarios 1 and 2 are preferred from a monetary point of view because of their low levels of total landed costs, but are not preferable when it comes to the scenario's features in terms of network and internal communication. A more expensive scenario such as scenario 3 is able to support a better infrastructure for the communication within the network as well as inside each production side. Especially for production networks where complex products are manufactured using extensive production processes such as in the case of a gear box producer, considering a communication-optimized scenario (scenario 1 or 3) rather than a solely cost-optimized scenario (scenario 2) can outperform the cost savings in terms of meeting the company's complexity handling goals.

6. Conclusion

Management and design of global production networks are a major challenge for each company. Therefore, tools are required to support the assessment of possible network scenarios and to help making decisions based on specific goals of a company. The assessment methodology in this paper supports the evaluation process of different network scenarios. However, it is not an absolute solution applicable for any kind of network design decision. It rather is an additional tool to consider "soft" factors such as complexity and communication and has to be interpreted case by case.

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References

- [1] IBM, 2010. Unternehmensführung in einer komplexen Welt - Global CEO Study. Executive Summary. IBM Deutschland GmbH, pp.2-3.
- [2] Iyengar, S., 2011. How to make choosing easier. TEDSalon NY2011, available: http://www.ted.com/talks/sheena_iyengar_choosing_what_to_choose.html
- [3] Malik, F., 2002.. Strategie des Managements komplexer Systeme. Haupt, Bern, Switzerland, pp. 184-209.
- [4] Beishon, J., 1980. System Organization: The Management of Complexity - Introduction to systems thinking and organization. Open University, Milton Keynes, Great Britain.
- [5] Kirchhof, R., 2003. Ganzheitliches Komplexitätsmanagement - Grundlagen und Methodik des Umgangs mit Komplexität im Unternehmen. Deutscher Universitäts-Verlag, Wiesbaden, Germany, pp. 8-24.
- [6] Reiss, M., 1993. Komplexitätsmanagement I. WISU, vol. 22, no.1, pp. 54-60.
- [7] Klaus, G., Liebscher, H., 1974. Wörterbuch der Kybernetik. Fischer, Frankfurt a. M., Germany, pp. 307-308.
- [8] Kornwachs, K., von Lucadou, W., 1975. Beitrag zum Begriff der Komplexität. Grundlagenstudien aus Kybernetik und Geisteswissenschaft, vol. 16, no. 2, pp. 51-60.
- [9] Krieg, W., 1971. Kybernetische Grundlagen der Unternehmensgestaltung. Haupt, Bern, Switzerland, pp. 44-50.
- [10] Shannon, C. E., 1976. Die mathematische Theorie der Kommunikation, in „Mathematische Grundlagen der Informationstheorie“ C.E. Shannon, W. Weaver, Editors. Oldenbourg, München, Germany, pp. 41-76.
- [11] Luhmann, N., 1984. Soziale Systeme - Grundriß einer allgemeinen Theorie. Suhrkamp, Berlin, Germany, p.236-240.
- [12] Allen, T., Henn, G., 2007. The Organization and Architecture of Innovation - Managing the Flow of Technology. Elsevier, Burlington, USA, p. 85-86.
- [13] Dunbar, R., Barrett, L., Lycett, J., 2005. Evolutionary psychology - a beginner's guide human behaviour, evolution and the mind. Newworld, Oxford, Great Britain, p.92-100.
- [14] Schuh, G., Potente, T., Kupke, D., Varandani, R., Hausberg, C., 2012. An Evolutionary Approach for Global Production Network Optimisation. Proceedings of the 45th CIRP Conference on Manufacturing Systems 2012, pp. 383.
- [15] Merchiers, A., 2008. Bewertung globaler Standortstrukturalternativen im Maschinenbau. Apprimus, Aachen, Germany
- [16] Ude, J., 2010. Entscheidungsunterstützung für die Konfiguration globaler Wertschöpfungsnetzwerke - Ein Bewertungsansatz unter Berücksichtigung multikriterieller Zielsysteme, Dynamik und Unsicherheit. Shaker, Aachen, Germany
- [17] Lanza, G., Moser, R., Scholz-Reiter, B., Özşahin, M-E., Schukraft, S., Meil, P., Rasp, F., 2011. Planung und Optimierung wandlungsfähiger globaler Wertschöpfungsnetzwerke. Industrie Management, vol. 27, no. 3, pp. 57-60.
- [18] Vliegen, R., van Wijk, J., van der Linden, E-J., 2006. Visualizing Business Data with Generalized Treemaps. IEEE Transactions on Visualization and Computer Graphics, vol. 12, no. 5, p.780-796
- [19] Pentland, A. 2012. Kommunikation ist der Schlüssel. Harvard Business Manager, no.5, pp.41-44.